The Journal of Global Radiology

ENSURING MEDICAL IMAGING ACCESS FOR ALL

ORIGINAL RESEARCH

The Use of Local Alternative Materials as Structural Shielding for Diagnostic Radiological Facilities

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OPEN ACCESS

DOI: 10.7191/jgr.2020.1050

Published: 2/5/2020

Citation: Sagon S, Surujpaul PP. The Use of Local Alternative Materials as Structural Shielding for Diagnostic Radiological Facilities. J Glob Radiol. 2020;6(1):1050.

Keywords: Alternative materials, lateritic soil, clay soil, structural shielding, radiation shielding, radiation protection

Word count: 3,405

ISSN 2372-8418

Abstract

Purpose: X-ray radiation shielding is based on the principle of attenuation, which is the ability to reduce the initial intensity of radiation through a barrier material. The research aimed to obtain the most efficient shielding material to attenuate ionizing radiation in the diagnostic range (0-150 kV) using locally available clay soil, lateritic soil and white sand combined with Portland limestone cement.

Methods and materials: A mix design was used to determine the mix ratio that would attain the highest density and compressive strength, hence more suitable for radiation protection. Sample blocks of dimensions 20 cm x 15 cm and thicknesses 4 cm, 8 cm, 12 cm, 16 cm and 20 cm were prepared. Using a RayMax Medical Corp conventional x-ray machine and RaySafe X2 dosimeter, in narrow beam geometry, kerma readings were obtained at energy output of 46.5 kVp, 65.3 kVp, 84.1 kVp, 102.5 kVp, 120.9 kVp and 134.5 kVp without the presence of any block, then with blocks in the path of the beam. The percent transmission for each block type and thickness at the measured X-ray energy was calculated.

Results: Blocks that preserved a lower cement to aggregate ratio attained a higher density and compressive strength. Percentage transmission was reduced from 100 % to below 10 % with the presence of each block thickness.

Conclusion: Blocks composed of cement and white sand and cement and clay soil, with mix ratios of 1:3 for the former and 1:3 and 1:4 for the latter, can be used as structural shielding. Of the mixtures, cement and white sand attained the highest density and compressive strength, however, cement and clay soil proved to be most stable, both in its engineering properties and attenuating ability.

Introduction

The use of x-rays plays a significant role in the clinical diagnosis and treatment of patients. Diagnostic imaging delivers low-level radiation. Even such a low exposure poses an unknown probabilistic risk (stochastic effects) to the patient, personnel and members of the general public. Adequate protective measures are, therefore, mandated to include structural shielding. Any material, when placed in sufficient thickness, can serve to reduce or attenuate radiation. However, a good shielding material should have a high attenuation coefficient due to high physical density (1). Traditionally, lead has been the material of choice for radiation shielding because of its high density and atomic number, hence minimal thickness required. However, lead is not produced locally in Guyana, thus is not readily available and its import is expensive. Further, the production of lead has raised concerns because of health risks associated with its toxicity and effects on the environment. Disposal or recycling of lead from decommissioned x-ray facilities may be costly, and in some instances this may not be done properly.

As an alternative to lead, concrete, a mixture of cement, fine aggregate (usually sand), large aggregate (stone) and water is one of the most common materials used as structural shielding in radiological facilities (2). Concrete is advantageous because its density can be easily manipulated to achieve a lead equivalence, it has the ability to maintain its compressive strength, and it can be fabricated on site. Researchers have also shown that other aggregates may be added to enhance the attenuating ability of the concrete (3-6). Using the physical properties of these materials, a mixture may be produced inexpensively to provide adequate radiation shielding.

In developing countries, researchers have been conducting studies on local soils as an inexpensive alternative to concrete and other building materials (7-9). The effectiveness of laterite and clay as radiation-shielding materials have also been examined (10).

However, differences of opinion exist among experts regarding the definition and classification of laterite and clay. These classifications are based upon morphology, physical appearance, engineering properties and chemical composition (11,12). For the purposes of this study, the terms lateritic soil and clay soil were used only with reference to the physical appearance of the materials.

In radiation protection, the linear attenuation coefficient (μ) is the most commonly used mathematical value that determines the penetration and dispersal of radiation within a medium (13). The concept states that a material with thickness x placed in the path of a beam will attenuate the beam according to the Beer-Lambert law, given by the formula:

$$I = I_0 e^{-\mu x} \tag{1}$$

where I_o and I are the unattenuated and attenuated photon intensities respectively, and μ (cm^{-1}) is the linear attenuation coefficient of the material.

The linear attenuation coefficient derived from equation (1) can be stated as:

$$\mu = \frac{\ln\left(\frac{I_0}{I}\right)}{x} \tag{2}$$

Guyana has seen an increase in the number of private health facilities, many of which offer x-ray services. International standards require lead or lead-equivalent concrete for shielding at diagnostic radiological facilities (14,15). However, due to the difficulties in procuring lead, there is a need for alternatives that are easily accessible and inexpensive.

The purpose of this study was to investigate the ability of locally available and cost-effective materials to attenuate ionizing radiation in the diagnostic range that can be used as an alternative to lead and concrete as structural shielding.

Methods and materials

Preparation and testing of materials

White sand, clay soil and lateritic soil were extracted from existing pits within Linden, Guyana (located 6°00′20.2″N 58°19′57.1″W, 6°01′34.0″N 58°18′37.2″W and 5°57′20.7″N 58°23′24.2″W respectively) because of the physiological abundance of the materials within that geographic region.

Initial drying of the mined material was performed under atmospheric conditions and agglomerated particles loosened using a pestle and mortar. Further drying was done in a dry oven at a temperature of 103 ^{0}C.

Masses of the white sand, clay soil, lateritic soil and Portland limestone cement were measured using a digital balance (accurate to 0.1 g) and volume determined by water displacement method using a calibrated measuring cylinder. The density of each material was calculated by the formula:

$$\rho = \frac{m}{v} \tag{3}$$

where ρ is the density, **m** and **v** are the mass and volume, respectively.

Sieve Analysis

Dry sieve analysis and classification of white sand, clay soil and lateritic soil were performed using American Standard test sieves and a digital balance in accordance with ASTM-C136-84A (16). The percent passing or finer was plotted against the sieve size on a semi-logarithmic graph (gradation curve). The effective particle size, coefficient of uniformity (C_u) and coefficient of curvature (C_c) were calculated as:

$$C_u = \frac{D_{60}}{D_{10}} \tag{4}$$

$$C_c = \frac{D_{30}^{\,2}}{D_{10} \times D_{60}} \tag{5}$$

where D_{60}, D_{30} and D_{10} are the diameter in the particle-size distribution curve corresponding to 60%, 30% and 10% passing, respectively.

Block preparation

Mix design

A mix design was used to determine the mix ratio that would attain the highest density and compressive strength, making the mixture more suitable for radiation protection. Clay soil, lateritic soil and white sand were mixed with Portland limestone cement by volume replacement, using mix ratios of 1:3, 1:4 and 1:5 (cement to aggregate). Using a trowel and mixing pan, the dry components were mixed until well blended, then clean tap water added to achieve workability and the mixture molded into cubes (Table 1). Sample blocks for transmission tests were then prepared using the mix ratio that attained the highest density and compressive strength (Table 2).

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Molding and curing

A quantity of each mixture was placed in wooden molds designed to achieve the various thicknesses of each batch of blocks. The moulds were lightly oiled to facilitate easy removal of the block. The mold was filled to approximately one third volume, then compacted using a tamping rod in accordance with the British Standard 1377:1990 (17). The mold was filled in three equal layers and the surface of the compacted mix levelled off the top with a straight edge.

After twenty-four hours, the blocks were removed from the molds and placed on construction plastic, taking special care when extruding the samples from the mold to preserve physical intactness of the block.

The extruded samples were left to cure under atmospheric conditions in a controlled environment. The curing process entailed wetting daily with water for 28 days.

Density measurement

The mass of the blocks prepared at Table 1 were assessed using a digital balance, volume determined from the product of the length, width and height dimensions measured with a Vernier caliper. Density was then calculated using equation (3).

Compressive strength test

On the twenty-eighth day, the compressive strength of the blocks outlined in Table 1 was determined using an ELE Hyson, No. 1317859 compressive strength testing machine in accordance with ASTM C109 (18). The compressive strength of the samples was calculated using the formula:

$$\textbf{(6)} \qquad \frac{\textbf{maximum load (pounds)}}{\textbf{cross-sectional area (inch)}^2}$$

The average compressive strength in pounds per square inch (psi) for each mix ratio was then determined.

Determining transmission factors

The experimental setup was as shown in Figure 1. A RayMax Medical Corp (Brampton, ON, Canada) fixed conventional x-ray machine (Model 2136, Serial Number 2878; energy range of 40 to 145 kVp; manufactured May 2004) and a RaySafe (Billdal, Sweden) X2 dosimeter with radiography/fluoroscopy sensor, which was able to give instantaneous readings for kVp, dose, dose rate and filtration (HVL), were used in the experiment.

A spirit level was used to ensure that the surface of the table and the x-ray tube head were flat (180^0). With the aid of a meter rule, the RaySafe X2 detector was placed 60 cm away from the focal spot of the x-ray tube. This distance was to reduce loss in x-ray intensity associated with the inverse square law. With the guidance of the collimator light, an x-ray field was collimated to 3 cm x 3 cm to ensure coverage of the sensitive window of the detector.

To determine the tube output behavior, parameters of 50 kVp and 120 mAs were set on the control panel. An exposure was made and the tube output measured by the RaySafe detector. This step was repeated at energy potentials of 70 kVp, 90 kVp, 110 kVp, 130 kVp and 145 kVp with constant mAs of 120.

Kerma (Kinetic Energy released per Unit Mass) values were obtained at distances denoted as Y_1, Y_2, Y_3, Y_4 and Y_5 (Figure 1) using the aforementioned exposure factors.

A block of thickness X_1 (Figure 1) was then placed anterior to the detector and another exposure made. The kerma transmitted through the block to the detector was recorded. This was repeated for blocks of thicknesses X_2, X_3, X_4 and X_5

Table 1. Specification of blocks prepared to test the mix design.

No.	Mixture type	Dimensions Length x Width x Height (cm)	Mix Ratio – Cement: Aggregate (volume replacement) Cement	Aggregate		
1	Cement + White sand	10 x 10 x 10	1	3	4	5
2	Cement + Lateritic soil	10 x 10 x 10	1	3	4	5
3	Cement + Clay soil	10 x 10 x 10	1	3	4	5

Table 2. Specification of blocks prepared for transmission tests.

No.	Mixture type	Mix ratio	Dimensions: Length x Height (cm)	Thickness (cm)				
1	Cement + White sand	1:3	20 x 15	4	8	12	16	20
2	Cement + Lateritic soil	1:3	20 x 15	4	8	12	16	20
3	Cement + Clay soil	1:3	20 x 15	4	8	12	16	20

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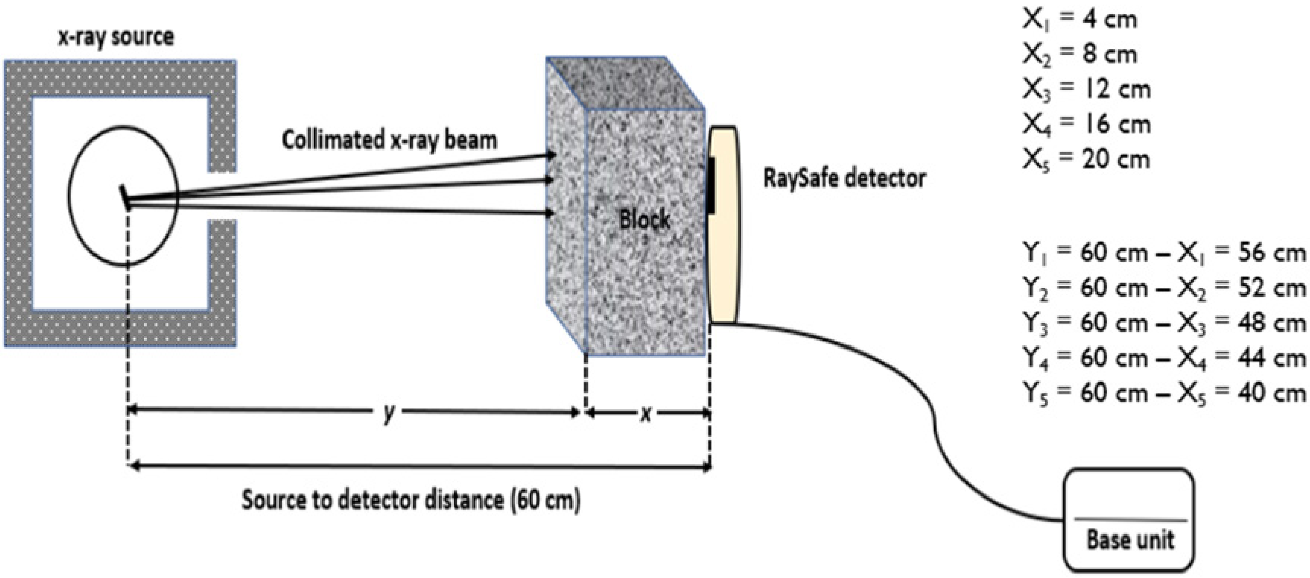
Figure 1. Experimental setup.

X_1, X_2, X_3, X_4 and X_5 represent the thickness of specimen blocks. Y_1, Y_2, Y_3, Y_4 and Y_5 represent the distance from the focal spot of the x-ray tube to the anterior surface of specimen blocks at the various thicknesses.



for cement and clay soil, cement and lateritic soil and cement and clay soil.

The values obtained for initial and transmitted doses during the transmission tests were recorded in milligray (mGy) for each sample type at the various thicknesses. It was then converted to milliroentgen (mR) using the formula (15,19):

$$\text{(7)} \qquad \mathbf{1\ mGy = 114\ mR}$$

then to intensity (I) by dividing the exposure (mR) by the tube current (mAs):

$$\text{(8)} \qquad I = \frac{\text{mR}}{\text{mAs}}$$

The percent transmission was determined as:

$$\text{(9)} \qquad \%\ \text{transmission} = \frac{\text{final intensity}}{\text{initial intensity}} \times 100$$

The percent transmission was plotted against block thicknesses at the measured x-ray tube output.

Results

The calculated density for white sand, lateritic soil, clay soil and Portland limestone cement were as shown in Table 3. Sieve analysis of white sand, lateritic soil and clay soil are presented in Figure 2. The average densities of specimen blocks prepared from cement and white sand at 1:3, 1:4 and 1:5 mix ratios were 2014.2 kg/m^3, 1969.8 kg/m^3 and 1943.2 kg/m^3 respectively; cement and lateritic soil were 1455.2 kg/m^3, 1419.7 kg/m^3 and 1322.1 kg/m^3 at 1:3, 1:4 and 1:5 mix ratios, respectively; and cement and clay soil were 1526.2 kg/m^3, 1508.4 kg/m^3 and 1437.4 kg/m^3 at 1:3, 1:4 and 1:5 mix ratios, respectively.

Table 3. Calculated density for white sand, lateritic soil, clay soil and Portland limestone cement used in the experiment.

Material	Density (kg/m^3)
White Sand	1177
Lateritic soil	1036.8
Clay soil	1021
Portland Limestone Cement	933

Table 4. Comparison of the x-ray tube output against the set x-ray potential at 120 mAs.

Tube current (mAs)	Set energy potential (kVp)	Measured tube output (kVp)
120	50	46.5
120	70	65.3
120	90	84.1
120	110	102.5
120	130	120.9
120	145	134.1

The average compressive strengths for cement and white sand blocks were 1146.3, 573, 154 psi at 1:3, 1:4 and 1:5 mix ratio respectively. Cement and clay soil blocks attained an average psi of 1058, 661 and 529, while cement and lateritic soil blocks attained 529, 441 and 132 psi at 1:3, 1:4 and 1:5 mix ratio respectively.

Table 4 gives the comparison of the set x-ray energy potential versus the measured tube output. Percentage transmission at the various block thicknesses and x-ray tube output were as shown in Figure 3 for cement and white sand, Figure 4 for cement and lateritic soil and Figure 5 for cement and clay soil.

Discussion

The white sand, clay soil and lateritic soil were all classified as uniformly or poorly graded sand (SP) in accordance to ASTM D2487 (20), having obtained a C_u of 2.33, 3.24 and 2.75 respectively and a C_C of 1.04, 0.78 and 0.89, respectively.

The density of the test blocks was controlled by changing the proportion of white sand, clay soil and lateritic soil to the concrete admixtures. As the proportion of aggregate to cement increased, the density of the block composite decreased. Of the three concrete admixtures, cement and white sand attained the highest average density, not significantly less than that of concrete, which has a density of 2400 kg/m^3. An admixture ratio 1:3 obtained the highest density of all.

The average compressive strength of the blocks varied by mixture type and mix ratio. The compressive strength as well as the average density decreased as the ratio of aggregate to cement increased. The average density obtained for each mixture type at 1:3, 1:4 and 1:5 mix ratio was well below the recommended 1900 psi by ASTM for loadbearing walls, but exceeded the 600 psi for non-loadbearing walls (21). Therefore, blocks prepared with 1:3 cement to white sand ratio and those of cement and clay soil with 1:3 and 1:4 mix ratios can be used for the construction of internal, non-loadbearing wall units.

This study proposes the elimination of large aggregates used in concrete mixtures. Using the nominal concrete mix method, a 1:3 (cement to fine aggregate) mix ratio would correspond to 6 parts large aggregate by volume replacement. The exact weight of the materials to be used can be determined using the Dry Loose Bulk Densities (DLBD) of materials and varies based on the source of the material. These calculations were beyond the scope of this study. However, an article in the local newspapers (22) quoted the price for stone in Guyana as ranging between US $36- US $40 per ton, a cost that would be completely eliminated using the proposed admixtures.

The percentage transmission was reduced from 100% without the presence of any block to below 10%, as blocks of 4 cm thickness were placed between the primary x-ray beam and the detector, corresponding to a percentage attenuation from 0% without blocks to over 90% with blocks. This was consistent for all the energies and for each mixture type.

Figure 2. Gradation curve foe sieve analysis of white sand, lateritic soil and clay soil.

D_{60}, D_{30} and D_{10} indicate 60 percent, 30 percent and 10 percent of the particles are finer than that diameter respectively. A steep curve would indicate that there is not a wide range of particle sizes in the sample and vice versa for a flat curve.

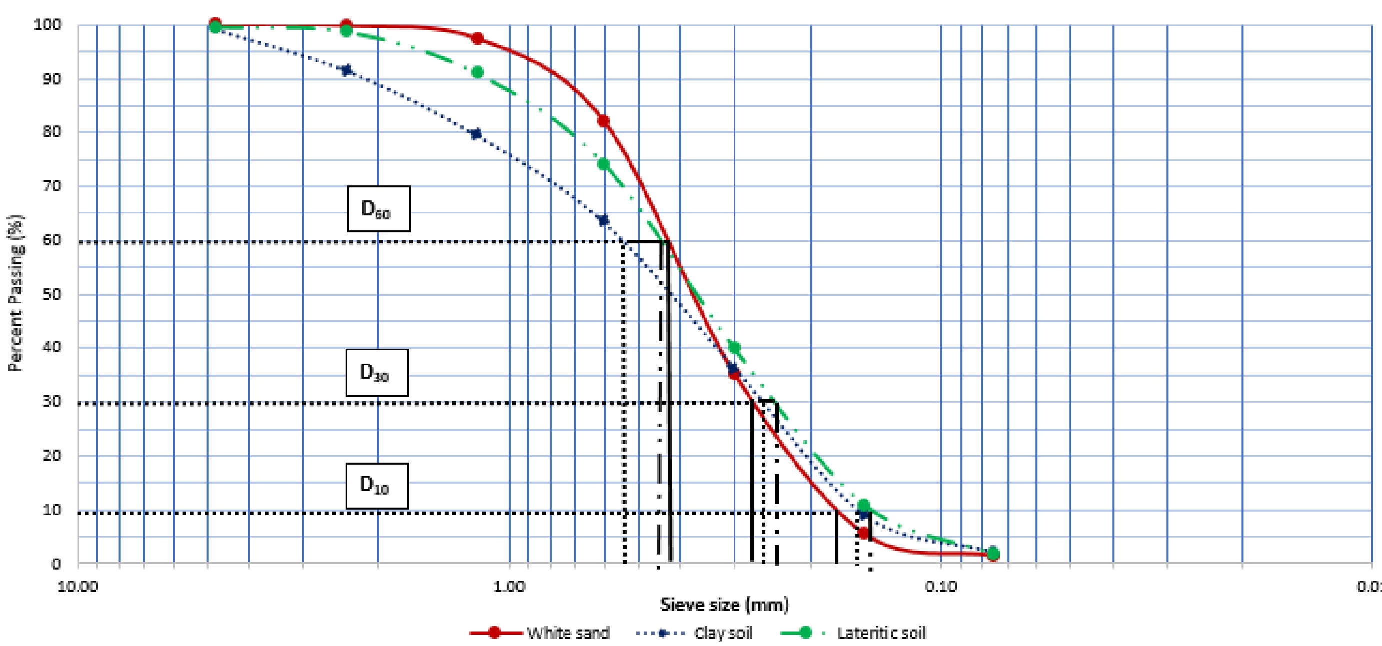


Figure 3. Percentage transmission plotted against block thickness at varying X-ray tube output for cement and white sand blocks.

Percentage transmission was reduced to below 10 percent with the introduction of block 4 cm thick. No transmitted kerma was detected through blocks thicker than 8 cm at X-ray tube output of 46.5 kVp.

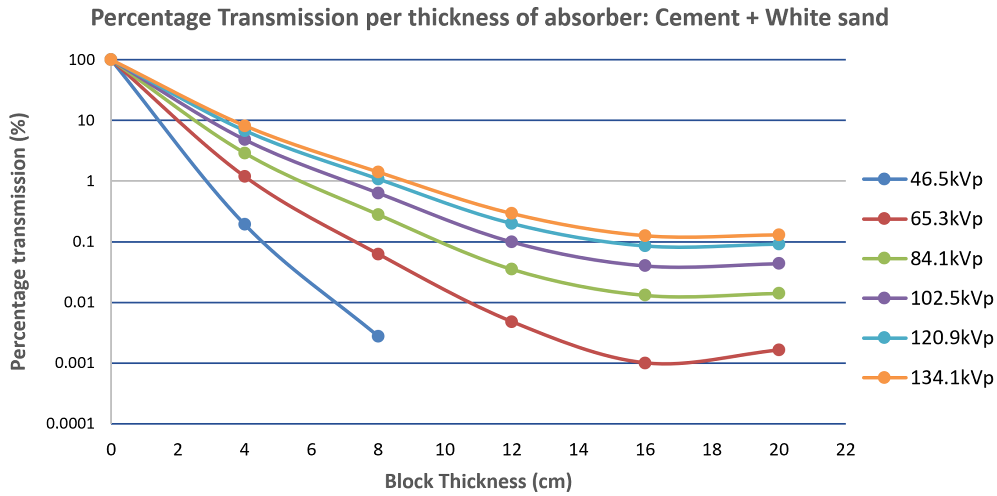


Figure 4. Percentage transmission plotted against block thickness at varying X-ray tube output for cement and lateritic soil blocks.

Percentage transmission was reduced to below 10 percent with the introduction of block 4 cm thick. No transmitted kerma was detected through blocks thicker than 8 cm at X-ray tube output of 46.5 kVp.

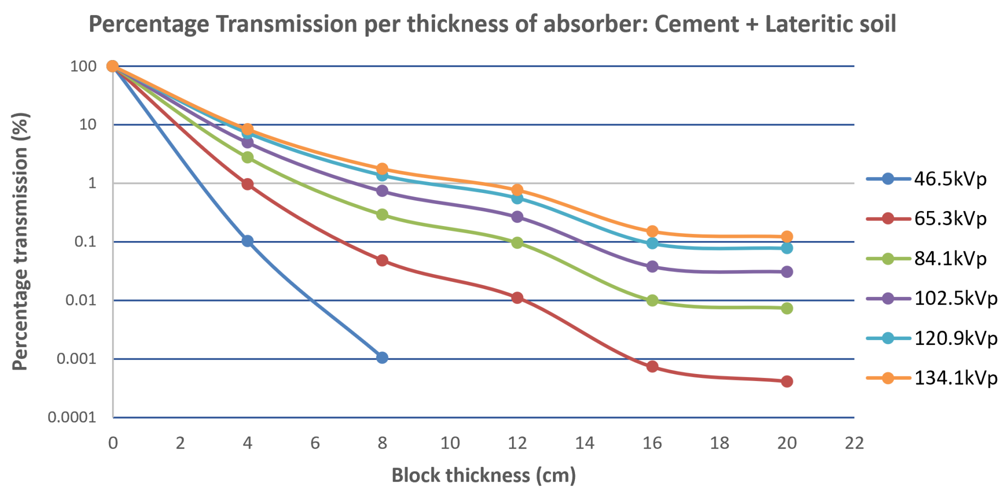
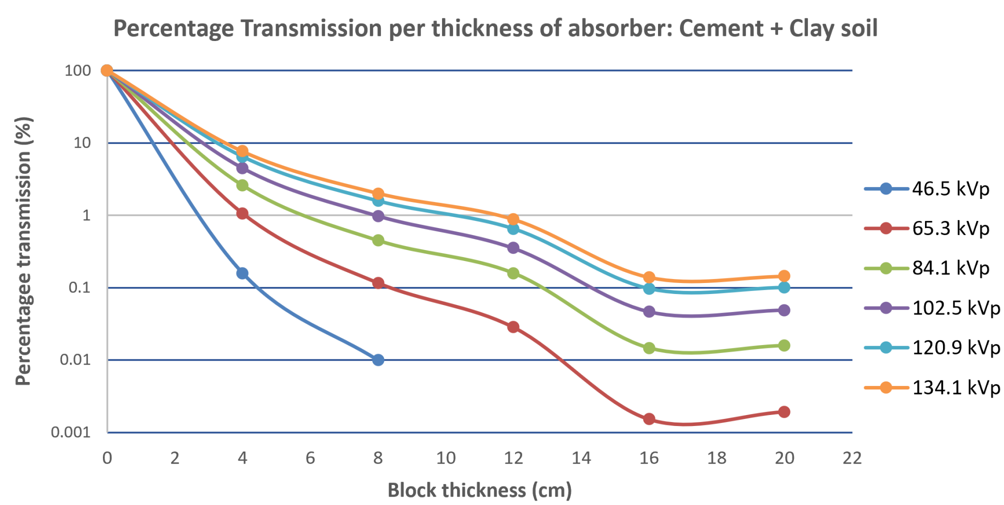


Figure 5. Percentage transmission plotted against block thickness at varying X-ray tube output for cement and clay soil blocks.

Percentage transmission was reduced to below 10 percent with the introduction of block 4 cm thick. No transmitted kerma was detected through blocks thicker than 8 cm at X-ray tube output of 46.5 kVp.



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Differences in the attenuating ability of each material could be attributed to the morphological characteristics and chemical composition of the individual materials.

Guyana is currently in the process of developing and adapting regulations directly relating to ionising radiation and its use in medical and non-medical facilities. However, the Ministry of Public Health is tasked with ensuring that facilities utilizing ionizing radiation are in compliance with international guidelines and regulations for the protection of occupationally exposed personnel and members of the public. Shielding design goals as outlined in NCRP Report 147 (14) are used to guide facilities in the design of barriers and is dependent on variables such as occupancy factor, use factor, workload and workload distribution of the individual facility. Hence, the appropriateness of the proposed admixtures as structural shielding materials is contingent on the facility.

Conclusion

All the proposed materials were able to effectively reduce the direct incidence of ionizing radiation to below 10% at the tested x-ray energies. However, only cement and white sand and cement and clay soil mixtures, at a 1:3 ratio for the former and 1:3 and 1:4 mix ratio for the latter, were able to meet the requirements for the physical construction of structural shielding.

Acknowledgments

The authors are thankful to the management of the Linden Hospital Complex and Georgetown Public Hospital Corporation X-ray Departments, and the Faculty of Technology-Civil Engineering, University of Guyana, for availing their facilities and equipment during this study.

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